

Postharvest UV-C treatment combined with 1-methylcyclopropene 1 (1-MCP), followed by storage in continuous low level ethylene atmosphere improves the quality of tomatoes

Authors:

Pristijono, Penta

Papoutsis, Konstantinos

Scarlett, Christopher J.

Bowyer, Michael C.

Vuong, Quan V.

Stathopoulos, Costas E.

Golding, John B.

- This is the accepted manuscript of an article published online by Taylor & Francis in the *Journal of Horticultural Science and Biothechnology* 28 March 2017 available online:
<http://dx.doi.org/10.1080/14620316.2017.1300512>

1 **Postharvest UV-C treatment combined with 1-methylcyclopropene (1-**
2 **MCP), followed by storage in continuous low level ethylene atmosphere**
3 **improves the quality of tomatoes.**

4

5 Penta Pristijono^{1*}, Konstantinos Papoutsis¹, Christopher J. Scarlett¹, Michael C. Bowyer¹,
6 Quan V. Vuong¹, Costas E. Stathopoulos³ and John B. Golding^{1,2}

7

8 ¹⁾ *School of Environmental and Life Sciences, University of Newcastle, Ourimbah, NSW*
9 *2258, Australia*

10 ²⁾ *NSW Department of Primary Industries, Gosford, NSW 2250, Australia*

11 ³⁾ *School of Science, Engineering and Technology, University of Abertay, Dundee DD1*
12 *1HG, UK*

13

14 *Corresponding author:

15 Dr Penta Pristijono

16 School of Environmental and Life Sciences

17 University of Newcastle

18 PO Box 127, Ourimbah - NSW 2258, Australia.

19 Ph: +61 2 4349 4783 Fax: +61 2 4348 4145

20 email: penta.pristijono@newcastle.edu.au

21

22 **Abstract**

23 Mature green tomatoes (*Solanum lycopersicum* cv Neang Pich) were exposed to
24 13.6 kJm⁻² UV-C or 0.5 µl l⁻¹ 1-MCP or combination of 13.6 kJm⁻² UV-C and 0.5 µl l⁻¹ 1-
25 MCP, with appropriate untreated controls. After treatment, tomatoes were stored in
26 continuous air containing 0.1 µl l⁻¹ ethylene at 20°C and 100% RH. The untreated fruit
27 ripened significantly faster than all other treatments. UV-C treatment alone was able to
28 delay fruit ripening by up to five days longer compared to untreated fruits whilst the
29 additional of 1-MCP further delayed fruit ripening. UV-C and 1-MCP treatments alone or
30 in combination had significantly slower ethylene production rates throughout the storage
31 period. The fruit treated with the combination of 1-MCP and UV-C was significantly
32 firmer and had higher in total phenolic content compared to the other treatments.
33 However, there was no difference between treatments in SSC/TA ratio, chlorophyll
34 content, lycopene content and total antioxidant activity. These results show that UV-C
35 and 1-MCP treatment delay ripening and improve the quality of tomatoes in the presence
36 of low level ethylene during storage. This new treatment could be used to extend the
37 shelf-life of mature green tomatoes through the supply chain without the use of
38 refrigeration.

39 **Keywords :** *Solanum lycopersicum*, ethylene, ripening, chlorophyll, lycopene, total
40 antioxidant, total phenolic content.

41

42 **Introduction**

43 The tomato is the world's most widely consumed vegetable (Scibisz et al., 2011). In many
44 countries, tomato production is largely aimed at the fresh-produce market and therefore
45 requires close management of ripening and the supply chain to ensure optimal external
46 and internal quality (De Oliveira et al., 2014).

47 Tomatoes are highly perishable and as for most climacteric fruits, anticipating
48 harvest before the climacteric rise is considered the best strategy to prolong shelf-life and
49 reduce the spoilage rate (Saltveit, 2005). However this practice can also negatively affect
50 taste and nutritional quality as fruit picked at the mature green stage or before turning to
51 red colour, although able to continue the ripening process, generally develop poor eating
52 and nutritional traits when fully ripened (Kader, 1986). The tomato fruit is composed
53 mainly of water, soluble and insoluble solids, organic acids (principally citric acid) and
54 micronutrients such as carotenoids and vitamins A and C (Pedro & Ferreira, 2007).
55 Sugars and organic acids are responsible for sweetness and tartness, and also influence
56 tomato flavour; as a result, they are the major factors affecting consumer acceptability
57 (Kader, 2008). Colour also has a marked influence on the initial purchasing decision by
58 consumers, who tend to link fruit colour to taste quality (Causse et al., 2010).

59 Treatment with UV-C (180 -280 nm) after harvest has been shown to reduce
60 pathogen growth (Guerrero-Beltrán & Barbosa-Cánovas, 2004) and has been reported to
61 extend the postharvest shelf-life of tomatoes by delayed fruit softening (Liu et al., 2011).
62 UV-C treatment has also been shown to delay ripening and senescence in table grapes
63 (Cantos & Tomás-Barberán, 2002), oranges (D'hallewin et al., 1999), peaches (Gonzalez-
64 Aguilar et al., 2004) and mangoes (Gonzalez-Aguilar et al., 2007). Therefore, postharvest

65 UV-C treatment has the potential to become a technological alternative to improve
66 storage of fruit and vegetables.

67 1-Methylcyclopropene (1-MCP) is an ethylene antagonist that widely used in
68 many horticultural industries (Blankenship & Dole, 2003). 1-MCP has been shown to
69 extend shelf-life, through fruit firmness maintenance, delaying carotenoid accumulation,
70 reducing respiration rate and ethylene production (Blankenship & Dole, 2003, and Cliff et
71 al., 2009). 1-MCP has been shown to be very effective in delaying ripening and in
72 extending the shelf life of tomatoes (Wills & Ku, 2002). Noting that UV-C treatment
73 induces ethylene synthesis (Stevens et al., 1998), and that this hormone could interfere in
74 the responses to UV-C, treatment unit of 1-MCP was applied to evaluate the impact of
75 UV-C treatment without the influence of ethylene. Previous study observed the
76 application of combination UV-C and 1-MCP, followed by storage in air at room
77 temperature (Tiecher et al., 2013 and Severo et al., 2015), they reported that combination
78 treatment of UV-C and 1-MCP delayed the tomato fruit degreening.

79 Ethylene is a ubiquitous in the storage environment (Wills et al., 2000), where the
80 ethylene levels in the supermarkets have been shown to be $0.017\text{--}0.035\ \mu\text{l l}^{-1}$ and greater
81 than $0.06\ \mu\text{l l}^{-1}$ in the wholesale markets and distribution centres. To date, there have
82 been no studies on UV-C treatments and in combination with 1-MCP followed by storage
83 in continuous low level ethylene atmosphere. Therefore, the objective of this study was to
84 evaluate the effect of UV-C treatment in combination with 1-MCP on tomato quality
85 during storage at 20°C with 100% RH, in continuous air containing $0.1\ \mu\text{l l}^{-1}$ ethylene.

86 **Materials and methods**

87 ***Produce***

88 Mature green or when fruits started to show the changed in incipient pink colouration at
89 the end of blossom tomatoes (*Solanum lypopersicum* cv Neang Pich) were harvested from
90 NSW Department of Primary Industries greenhouse (Ourimbah, N.S.W, Australia). Fruits
91 were hand-harvested from greenhouses in the cool of early morning to minimise
92 temperature differences at harvest. Tomatoes of uniform shape and size were taken to the
93 laboratory, weighed, randomised and sorted into experimental units of 20 fruits.

94 ***1-methylcyclopropene (1-MCP) and UV-C treatment and storage conditions***

95 The UV-C treatments were conducted using a custom made light proof box fitted with
96 two germicidal lamps (Sahkyo Denki Co. Ltd G20T10 20 Watt, Low Pressure Mercury).
97 A SED008/W detector with PIR Irradiance Calibration at 254 nm was used to monitor
98 UV-C intensity. UV-C intensity was determined prior to treatment by measuring the light
99 intensity (kJm^{-2}) using an International Light Technologies 1700 series research
100 radiometer. The applied dose (kJm^{-2}) was calculated by multiplying the emitting UV light
101 intensity with treatment time in seconds. Light intensity was evaluated several times
102 during the experiments to ensure consistent output. The tomatoes were placed
103 approximately 15 cm from the UV-C light sources on one side then rotated 180°C and
104 exposed again to ensure complete coverage; and during 12 min treatment received 13.6
105 kJm^{-2} of radiation. UV-C irradiation treatment was carried out at room temperature ($20 \pm$
106 1°C) and relative humidity at 79%, unless otherwise stated.

107 In order to block the ethylene action, $0.5 \mu\text{l l}^{-1}$ 1-MCP was applied in a 60 l sealed
108 jar 24 h at 20°C and 85% RH, using SmartFresh powder (AgroFresh Solutions Inc.,
109 Philadelphia, PA, USA) containing 0.34% 1-MCP as active ingredient. Treatments

110 consisted of fruit without UV-C or 1-MCP application (control), UV-C application at 13.6
111 kJm^{-2} , $0.5 \mu\text{l l}^{-1}$ 1-MCP and a combined 1-MCP + UV-C application under the same
112 conditions as when applied separately. For the combined treatment, UV-C was applied
113 24 h after the 1-MCP application. This unit treatment was performed to evaluate the effect
114 of UV-C treatment without the interference of ethylene. After treatment, all fruit were
115 stored in a constant atmosphere of $0.1 \mu\text{l l}^{-1}$ ethylene to provide simulated storage
116 conditions at 20°C and 100% RH. Treatment unit was 20 tomato fruits.

117 ***Determination of fruits quality attributes***

118 Tomato quality (every day or every second day) was measured weight loss, ethylene
119 production, respiration rate, and skin colour. Tomatoes were also assessed for firmness,
120 soluble solids content (SSC) and titratable acidity (TA) when fully ripe. The chlorophyll,
121 lycopene, total phenols and total antioxidant were analysed at the beginning of the
122 experiment (day 0) and when tomatoes were fully ripe. The weight loss percentages were
123 calculated based on the initial weight of the tomatoes.

124 The colour was assessed according to the method of Tiecher et al. (2013).
125 Specifically, skin colour was measured by Hue angle using a Minolta colorimeter
126 (Minolta CR-400, Osaka), where the average of 3 points from calyx to blossom end were
127 measured. Hue angle ($^{\circ}\text{Hue}$) was calculated using the formula $^{\circ}\text{Hue} = \arctan (b^*/a^*)$.
128 The ethylene production and respiration were measured according to Pristijono (2007),
129 where tomatoes were transferred to a sealed 750 ml glass jars at 20°C, and after one hour
130 a gas sample (1 ml) was collected in a syringe and the ethylene and carbon dioxide
131 content were analysed. Ethylene was measured by injecting a gas sample into a gas
132 chromatograph (Gow-Mac 580, Bridgewater NJ). The ethylene concentration was

133 calculated with reference to the concentration of an ethylene standard. Ethylene
134 production was calculated as $[(C_2H_4 (\mu l l^{-1}) \times \text{volume (ml)}) / (\text{weight (kg)} \times \text{Time (h)})]$,
135 and expressed as $\mu l C_2H_4.kg^{-1}.h^{-1}$. Carbon dioxide concentration was measured to within
136 0.1% using an ICA40 series low volume gas analysis system (International controlled
137 Atmosphere Ltd., Kent, UK). Respiration rate was calculated as $[(CO_2 (\%) \times \text{volume}$
138 $(ml)) / (\text{weight (kg)} \times \text{Time (h)} \times 100)]$ and expressed as $ml CO_2.kg^{-1}.h^{-1}$.

139 Tomato firmness was determined as the maximum force (Lloyd texture analyser,
140 Fareman, UK), required to push a 7 mm probe into the fruit flesh to a depth of 2 mm. The
141 average of 2 reading points from each side of the fruit was taken. Results were expressed
142 in Newton (N). The soluble solid content (SSC), expressed as °Brix, was measured
143 according to Pataro et al. (2015), with slight modifications where sample were collected
144 from the pressed juice of fruit by means of a hand refractometer (ATAGO Inc., Bellevue,
145 WA, USA). Titratable acidity (TA), expressed as % citric acid, was determined by
146 titrating 3 ml tomato supernatant to pH 8.2 with a 0.1 N NaOH solution using an
147 automatic titrator (Mettler Toledo T50, Switzerland).

148 ***Chemical analysis and antioxidant activity evaluation***

149 Three tomatoes were randomly selected from each treatment units, at the beginning of the
150 experiment and after each fruit was fully ripe. After sampling, tomatoes were sliced into
151 small pieces discarding the top and bottom sections and immediately stored at $-20^{\circ}C$
152 until further analysis. The frozen samples were later analysed for chlorophyll, lycopene
153 content, total phenolic content and total antioxidant activity.

154 ***Total chlorophyll and lycopene content***

155 Total chlorophylls and lycopene were estimated according to the method of Lichtenthaler
156 and Wellburn (1983). Specifically, 1 g of blended sample was mixed with 10 ml 100%
157 acetone in test tubes and held at -20°C for 48 h. The samples were then vortexed,
158 centrifuged at $10,000 \times \text{rpm}$ for 10 min at 20°C and then the supernatants were filtered
159 through Whatman No 1 filter in volumetric flasks of 25 ml. Subsequently, 10 ml 100%
160 acetone were added to the precipitate and the samples were shaken at $150 \times \text{rpm}$ for 10
161 min. The samples were again filtered and added at the previous volumetric flasks, which
162 were completed with 100% acetone and the absorption was determined
163 spectrophotometrically at 652 nm. The following formula was used for the calculation of
164 total chlorophyll and lycopene based on the study by Arnon (1949); Total chlorophyll
165 (mg l^{-1}) = $D_{652} \times 1000/34.5$, where D_{652} is the absorbance at 652 nm and 34.5 is the
166 value of the specific absorption coefficient at 652 nm. The following formula was used
167 for the calculation of lycopene; Lycopene: (mg g^{-1}) = ($\text{Abs } 503 \times \text{Volume (ml)}$) $\times 3.1212$
168 / Weight (g)). Where A_{503} the absorbance at 503 nm and 3.12 is the extinction
169 coefficient.

170 *Total phenolic content*

171 The total phenolic content was measured by the Folin–Ciocalteu method as described by
172 Singleton and Rossi (1965) and the results were expressed as mg gallic acid equivalents
173 (GAE) per 100 g of fresh weight ($\text{mg GAE } 100^{-1} \text{ g FW}$).

174 *Total antioxidant activity*

175 DPPH radical scavenging activity was determined according to Brand-Williams et al.
176 (1995), with slight modifications. Specifically, 200 μl of the extracted sample were added

177 to 2800 µl 100 µm 2,2-diphenyl-1-picrylhydrazyl (DPPH) methanolic solution, it was
178 vortexed and maintained in dark and at 20°C for 1 h. Absorbance was measured at 517
179 nm. The percentage of DPPH[•] scavenging is calculated according to the equation of %
180 DPPH scavenging = 100 × (control absorbance – sample absorbance / control
181 absorbance).

182 ***Statistical analysis***

183 The experimental design was completely randomized, consisting three UV-C treatment
184 units (a) control (without UV-C or 1-MCP), (b) UV-C, (c) 1-MCP and (d) UV-C + 1-
185 MCP. The experiments were replicated three times. The one-way ANOVA and the Least
186 Significance Difference (LSD) were conducted using the SPSS statistical software
187 version 22. Data were reported as means ± standard deviations. Differences between the
188 mean levels of the components in the different treatments were taken to be statistically
189 significant at $p < 0.05$.

190 **Results and discussion**

191 Tomatoes at the mature green stage or when the fruits had just started to show incipient
192 pink colouration at the end of blossom tomatoes stage were used since this represents the
193 stage at which they are usually harvested in order to minimize loss during transport and
194 storage. Skin colour values determined before each of the three replicate experiments
195 showed only slight differences among the three batches used. Hue angle (°Hue) is one of
196 the appropriate ripening indexes in tomato (Lopez Camelo & Gomez, 2004) and the
197 results did not show significant differences ($p < 0.05$) between batches denoting
198 homogeneity in terms of maturity level. Not surprisingly, the average initial lycopene

199 content (mg/g f.w) was low and high in chlorophyll content (mg l⁻¹). Ethylene
200 production, respiration rate, SSC, TA, fruit firmness, total phenolic content and
201 antioxidant activity of tomatoes at harvest is presented in Table 1.

202 ***Effect on weight loss***

203 Weight loss of tomatoes was measured when the fruits were fully ripe (°Hue = 60.4), and
204 with the results showing that the tomatoes treated with UV-C alone did not significantly
205 affect weight loss during ripening (Figure 1A). The 1-MCP treatment and combined
206 treatment of 1-MCP + UV-C fruits showed a significantly ($p < 0.05$) lower in weight loss
207 than UV-C treatments or control fruits, however the weight loss was only 0.2 % lower
208 compared to control fruits and not to be considered commercially significant. This result
209 contrary to Pinheiro et al., (2015) who found that tomatoes treated with 4.83 kJm⁻² UV-C
210 showed lower levels of weight loss of fruits after 15 d storage at 10°C, than untreated
211 UV-C fruits. The difference observed may be due to the storage conditions, where in this
212 study, after treatments the fruits were stored in air containing 0.1 µl l⁻¹ ethylene at 20°C,
213 with 100% RH until the fruits were fully ripe.

214 ***Effect on ethylene production***

215 Tomato is a climacteric fruit that is characterised by increased ethylene production and
216 continued ripening after harvest (Cara & Giovannoni, 2008). The results of this
217 experiment showed that UV-C, 1-MCP and 1-MCP+UV-C treatments slowed ethylene
218 production, while control fruit had concluded the ethylene climacteric peak in 6 d, the
219 UV-C or 1-MCP or 1-MCP+UV-C treated fruit after 6 d storage still had elevated
220 ethylene production which indicated that fruit were not completely ripe (Figure 2A). In

addition, the maximum climacteric peak was delayed by 3 d with UV-C or 15 d with 1-MCP treatments. The combination treatment of 1-MCP prior to UV-C was able to delay the climacteric by 12 d which explained that the application of 1-MCP prior to UV-C was unable to promote ethylene production. These results also show that the UV-C treatment delayed ripening in tomatoes by inhibiting ethylene production during storage. These results in accord with the previous report by Tiecher et al. (2013) who found that tomatoes treated with 3.76 kJm^{-2} still had elevated ethylene production after 7 d storage in air. The delay in ethylene production also affected the development of the red colour where untreated tomato fruit changed colour quicker than fruit treated with UV-C, 1-MCP or 1-MCP +UV-C. It should be noted that in this experiment the storage environment contained $0.1 \mu\text{L.L}^{-1}$ ethylene to stimulate commercial storage conditions. These results are consistent with those previously reported by Stevens et al. (1998) and Maharaj et al. (1999) observed a reduction of ethylene production in tomatoes treated with UV-C. These results suggest that the UV-C treatment irradiation extends the postharvest life of tomatoes by delaying the peak ethylene production and fruit ripening.

Effect on skin colour

The most visible symptom of tomato ripening is the change in skin colour from green to red, where the Hue value of a typical tomato fruit will decrease as the ripening process progresses (Jagadeesh et al. 2011). Tomato colour (Hue values) changed during storage are shown in Figure 2B, where at day 0, all samples were described as green colour (high Hue values). The tomatoes treated with 13.6 kJm^{-2} UV-C alone or $0.5 \mu\text{l l}^{-1}$ 1-MCP alone or the combination of 13.6 kJm^{-2} UV-C and $0.5 \mu\text{l l}^{-1}$ 1-MCP produced significant delays in colour change. Untreated fruits fully ripened and became red 6 d after harvest while

UV-C treated fruit became fully red 11 d after harvest, whilst fruits from the combined treatment of 1-MCP + UV-C, became fully red within 17 d after harvest. As expected, 1-MCP treated fruits were the longest period to become fully red within 21 d. Even though, there was difference in the storage conditions with previous study, where the fruit was stored in air at room temperature, but this result was consistent with the finding by Tiecher et al. (2013) and Severo et al. (2015) who reported that the application 3.7 kJm^{-2} UV-C maintained the green colour of tomatoes, and combination treatment of $2 \mu\text{L.L}^{-1}$ 1-MCP and 3.7 kJm^{-2} UV-C further inhibit colour change, and retained a higher hue values. Also, Liu et al. (2009) observed that after tomato treated with 13.7 kJm^{-2} UV-C, followed by storage in air with fans continuously circulating air across the tomatoes, they found that a high Hue value was obtained on UV-C treated fruits after 21 d storage at 14°C . This result suggests that UV-C treatment alone or in combination with 1-MCP delayed the tomato degreening regardless the storage conditions.

Effect on firmness

Fruit firmness was evaluated when the tomatoes were fully ripe (6 d for control, 11 d for UV-C treated, 17 d for 1-MCP+UV-C treated and 21 d for 1-MCP treated fruits). The results showed that the highest firmness was maintained in the combined treatment of 1-MCP + UV-C treated fruit followed by 1-MCP alone, UV-C alone and untreated fruit (Figure 1B). The UV-C treatment did not contribute to flesh firmness preservation. However, combining 1-MCP and UV-C treatments produced significantly firmer fruits than UV-C treatment alone or when compared to control. This result confirms that 1-MCP treatment contributed to maintaining flesh firmness in tomato (Jeong et al., 2002). Moreover, comparing untreated and UV-C treated fruits, there was no significant in fruit

firmness ($p < 0.05$). These results were contradictory with the previous report of Barka et al., (2000) and Stevens et al., (2004) who reported that tomato firmness was significantly increased by low-dose UV-C treatment, and that cell-wall degrading enzyme activities were also decreased. Also, Liu et al. (2009) reported that tomato firmness was significantly decreased by UV-C treatment. This experiment result suggest that UV-C treatment acts more in colour (degreening and reddening) than in firmness changes of tomatoes.

Effect on TSS, TA and TSS/TA ratio

SSC and TA were measured on fully ripe fruits and the result shows that SSC and TA were not affected by UV-C, 1-MCP treatments alone or the combination treatment of 1-MCP + UV-C (Table 2). These results are consistent with those previously reported by Liu et al., (2009) who observed that SSC did not change in tomatoes (cv Red Ruby) after treatment with 22.8 W.m^{-2} UV-C lights stored at $12 - 14^{\circ}\text{C}$ for 21 d. However, other reports have shown that tomatoes treated with 3.7 kJ.m^{-2} UV-C followed by storage at 15°C for 15 d produced lower sugar content and higher in TA than untreated fruits (Charles et al., 2016). These differences may be due to the assessment of sugar content, where in this experiment SSC and TA were measured, while the previous report measured the total simple sugar of glucose, fructose and sucrose, as well as total organic acid were measured.

The SSC/TA, or sugar to acid ratio is an important taste factor and an indicator of maturity, ripeness, or both in some mature fruit-type vegetables such as tomato (Malundo et al., 1995). Loss of sensory quality in tomatoes is associated with reduction of sweetness and acidic taste (Grierson & Kader, 1986). In this experiment, the SSC/TA showed no

290 significant difference between untreated fruits and all other treatments (Table 2). These
291 results suggest that UV-C treatments, alone or in combination with 1-MCP, did not have
292 any effect on SSC to TA ratio in tomato.

293 *Effect on total chlorophyll and lycopene content*

294 Colour change in fruit which including chlorophyll degradation is closely associated with
295 the chloroplast transition to chloroplast, which regulated by ethylene (Barsan et al., 2010).
296 In this study, Total chlorophyll content was measured when tomatoes were fully ripe. The
297 result shows that there were not statistically different in total chlorophyll content between
298 treated and untreated fruits (Figure 3A). However untreated tomatoes showed higher
299 chlorophyll content than UV-C treated fruits, which potentially UV-C treatments induced
300 chlorophyll degradation, and when comparing UV-C treatments and 1-MCP treatment
301 alone or the combination treatment of 1-MCP + UV-C show that UV-C treated fruits had
302 lower chlorophyll content than fruits treated with combination of 1-MCP + UV-C or 1-
303 MCP alone. This may suggest that 1-MCP prevented chlorophyll degradation during
304 ripening, which may also indicate that chlorophyll degradation is ethylene dependent.

305 Lycopene, is the major carotenoid present in the tomato fruit and is one of the
306 most important health attributes of tomatoes. The accumulation of lycopene during the
307 ripening process causes an increase in the redness of tomatoes (Li et al., 2016). In these
308 observations, after ripening at 20°C, all tomatoes were measured the lycopene content,
309 and the results show that there was no significant difference between untreated tomatoes
310 and all other treated fruits (Figure 3B). Moreover, the fruits treated with UV-C had
311 significantly higher lycopene content than 1-MCP treated fruits or combination treatment
312 of 1-MCP +UVC, and these results suggest that lycopene accumulation maybe partially

313 ethylene dependent, as even though UV-C treated fruits had low ethylene production
314 ($2.66 \mu\text{L C}_2\text{H}_4.\text{kg}^{-1}.\text{h}^{-1}$) but accumulated high lycopene content (35.1 mg/g f.w.). The
315 difference in lycopene content was potentially due to weight loss since the high lycopene
316 content was found in tomatoes with high weight loss (Figure 1A).

317 These results are in an agreement with the data reported by Tiecher et al., (2013)
318 who found that 1-MCP treatment inhibited total carotenoid accumulation including
319 lycopene. The increased lycopene content may be attributed to a pressure-induced
320 physiological stress during storage. Gonzalez-Aguilar et al. (2010) suggest that
321 postharvest treatments used to prolong fruit shelf-life such as high O_2 atmosphere,
322 irradiation, and heat treatments could induce changes in metabolic activity of the treated
323 produce, such as the triggering bioactive molecule synthesis. UV-C treatment during
324 storage may act in a similar manner.

325 ***Effect on total phenolic content (TPC)***

326 After ripening of tomatoes in air containing $0.1 \mu\text{l l}^{-1}$ ethylene at 20°C and 100% RH, the
327 total phenolic content was measured and the results showed that untreated tomatoes had
328 significantly lower TPC compared to other treatments (Figure 4A). The highest TPC was
329 found in the combination treatment of 1-MCP and UV-C, followed by fruits treated with
330 UV-C, 1-MCP alone, with an increase of 12%, 12% and 24% for UV-C, 1-MCP and 1-
331 MCP +UV-C treatments, respectively compared with the control.

332 These observations are consistent with those previously reported by Liu et al.,
333 (2011) who found that tomatoes treated with UV-C had highest levels of TPC. This
334 maybe due to general abiotic stresses which affect the pathways involved in biosynthesis
335 of the main three groups of secondary metabolites including terpenes, phenolic, and

nitrogen-containing compounds (Cisneros-Zevallos, 2003). Many studies have reported the enhancement of phenolic compound contents by environmental stress. For example, UV-C irradiation has been demonstrated to increase the levels of phenolics in several fruits such as tomato (Jagadeesh et al., 2011), apple (Dong et al., 1995), mango (González-Aguilar et al., 2007), and grape (Cantos et al., 2002). This may be a result of plant tissue induction of protective pathways to produce an accumulation of UV-light-absorbing flavonoids and other phenolics. In this study, 13.6 kJm⁻² UV-C treatment was found to enhance total phenolic content when the fruits were fully ripe, the further significant enhancement was found in icombined 3.6 kJm⁻² UV-C and 0.5 µl l⁻¹ 1-MCP treated fruits.

Effect on total antioxidant activity

After fruit ripening at 20°C, the DPPH antioxidant activity of fully ripe tomatoes was measured and the result is presented in Figure 4B. The result shows that there was no significant difference in DPPH activity between treated fruit and control. The main antioxidants in tomato are carotenoids, ascorbic acid, and phenolic compounds (Giovanelli et al., 1999). In this study, a 13.6 kJm⁻² UV-C, 0.5 µl l⁻¹ 1-MCP and combination treatment of 0.5 µl l⁻¹ 1-MCP and 13.6 kJm⁻² UV-C did not significantly affect DPPH scavenging activity during ripening periods even though the lycopene content was found to be higher by 11% in UV-C treated fruits than control. The relationship between lycopene and antioxidant activity is not always directly proportional, where the increase in lycopene content does not necessarily result in an increased antioxidant activity. In certain cases, an inverse relationship between antioxidant activity and lycopene content of red tomato varieties was observed at the end of the ripening stage

359 (Kotíková et al., 2011). The assessment of the single antioxidant assay indicated that an
360 increase in pure lycopene concentrations beyond critical levels could reduce scavenging
361 capacity values (Liu et al., 2008). However, its interactions with such other antioxidants
362 such as β -carotene, lutein, α -tocopherols could act either additively, synergistically or
363 antagonistically in scavenging free radicals (Zanfini et al., 2010).

364 **Conclusions**

365 The quality of fully ripe tomatoes was evaluated after the application of 13.6 kJm^{-2} UV-C
366 or $0.5 \mu\text{l l}^{-1}$ 1-MCP alone or the combination of $0.5 \mu\text{l l}^{-1}$ 1-MCP and 13.6 kJm^{-2} UV-C
367 followed by storage in air containing $0.1 \mu\text{l l}^{-1}$ ethylene at 20°C . Fruit ripening was
368 delayed by 3 d with UV-C treatment and further delayed when the application of 1-MCP
369 added. The combination treatment of 1-MCP and UV-C resulted in firmer fruits compared
370 to untreated fruits and UV-C or 1-MCP treated fruit alone. The level of TPC was
371 significantly affected by combination treatment of 1-MCP and UV-C, whereas there was
372 no difference in DPPH antioxidant activity. The ratio SSC to TA was not affected by the
373 treatments. Overall, the UV-C treatment combined with 1-MCP improved tomato quality
374 by delayed the fruits ripening and improved the firmness, as well as TPC. More study is
375 required to assess the effect of application of UV-C followed by 1-MCP, to determine if
376 the mode of action of UV-C is similar with this study.

377 **Acknowledgements**

378 This work was supported by the University of Newcastle, Australian Research Council
379 Training Centre for Food and Beverage Supply Chain Optimisation (IC140100032) and
380 NSW Department of Primary Industries. We are grateful to Josh Jarvis (NSW DPI) for

381 kindly growing the tomato fruit for this study. We acknowledge to Agrofresh Solution
382 Inc. for providing 1-MCP for this study.

383 **References**

- 384 Arnon, D. I. (1949). Copper enzymes in isolated chloroplasts. Polyphenoloxidase in *Beta*
385 *vulgaris*. *Plant Physiology*, 24, 1-15. doi: 10.1104/pp.24.1
- 386 Barka, E. A., Kalantari, S., Makhlouf, J., & Arul, J. (2000). Impact of UV-C irradiation
387 on the cell wall-degrading enzymes during ripening of tomato (*Lycopersicon*
388 *esculentum* L.) fruit. *Journal of Agricultural and Food Chemistry*, 48(3), 667-671.
389 doi: 10.1021/jf9906174
- 390 Barsan, C., Sanchez-Bel, P., Rombaldi, C., Egea, I., Rossignol, M., Kuntz, M., Zouine,
391 M., Latché, A., Bouzayen, M., and Pech, J.-C. (2010). Characteristics of the
392 tomato chromoplast revealed by proteomic analysis. *Journal of Experimental*
393 *Botany*, 61(9), 2413-2431. doi: 10.1093/jxb/erq070
- 394 Blankenship, S. M., & Dole, J. M. (2003). 1-Methylcyclopropene: a review. *Postharvest*
395 *Biology and Technology*, 28(1), 1-25. doi: [http://dx.doi.org/10.1016/S0925-](http://dx.doi.org/10.1016/S0925-5214(02)00246-6)
396 [5214\(02\)00246-6](http://dx.doi.org/10.1016/S0925-5214(02)00246-6)
- 397 Brand-Williams W., Cuvelier, M. E., & Berset, C. (1995). Use of a free radical method to
398 evaluate antioxidant activity. *LTW-Food Science and Technology*, 28, 25-30.
- 399 Cantos, E., Espin, J. C., & Tomas-Barberan, F. A. (2002). Postharvest stilbene-
400 enrichment of red and white table grape varieties using UV-C irradiation pulses.
401 *Journal of Agricultural and Food Chemistry*, 50(22), 6322-6329. doi:
402 10.1021/jf020562x

403 Cara, B., & Giovannoni, J. J. (2008). Molecular biology of ethylene during tomato fruit
 404 development and maturation. *Plant Science*, 175(1-2), 106-113. doi:
 405 10.1016/j.plantsci.2008.03.021

406 Causse, M., Friguet, C., Coiret, C., Lepicier, M., Navez, B., Lee, M., M., Holthuysen, N.,
 407 Sinesio, F., Moneta, E., and Grandillo, S. (2010). Consumer preferences for fresh
 408 tomato at the European scale: a common segmentation on taste and firmness.
 409 *Journal of Food Science*, 75(9), S531-541. doi: 10.1111/j.1750-
 410 3841.2010.01841.x

411 Charles, M. T., Arul, J., Charlebois, D., Yaganza, E. S., Rolland, D., Roussel, D., &
 412 Merisier, M. J. (2016). Postharvest UV-C treatment of tomato fruits: Changes in
 413 simple sugars and organic acids contents during storage. *Lwt-Food Science and*
 414 *Technology*, 65, 557-564. doi: 10.1016/j.lwt.2015.08.055

415 Cisneros-Zevallos, L. (2003). The use of controlled postharvest abiotic stresses as a tool
 416 for enhancing the nutraceutical content and adding-value of fresh fruits and
 417 vegetables. *Journal of Food Science*, 68(5), 1560-1565. doi: DOI 10.1111/j.1365-
 418 2621.2003.tb12291.x

419 Cliff, M., Lok, S., Lu, C., & Toivonen, P. M. A. (2009). Effect of 1-methylcyclopropene
 420 on the sensory, visual, and analytical quality of greenhouse tomatoes. *Postharvest*
 421 *Biology and Technology*, 53(1-2), 11-15. doi:
 422 <http://dx.doi.org/10.1016/j.postharvbio.2009.02.003>

423 de Oliveira, G. A., Bureau, S., Renard, C. M.-G. C., Pereira-Netto, A. B., & de Castilhos,
 424 F. (2014). Comparison of NIRS approach for prediction of internal quality traits in
 425 three fruit species. *Food Chemistry*, 143, 223-230. doi:
 426 <http://dx.doi.org/10.1016/j.foodchem.2013.07.122>

427 D'hallewin, G., Schirra, M., Manueddu, E., Piga, A., & Ben-Yehoshua, S. (1999).
 428 Scoparone and Scopoletin Accumulation and Ultraviolet-C Induced Resistance to
 429 Postharvest Decay in Oranges as Influenced by Harvest Date. *Journal of the*
 430 *American Society for Horticultural Science*, 124(6), 702-707.

431 Dong, Y. H., Mitra, D., Kootstra, A., Lister, C., & Lancaster, J. (1995). Postharvest
 432 stimulation of skin color in Royal gala apple. *Journal of the American Society for*
 433 *Horticultural Science*, 120, 95-100.

434 Giovanelli, G., Lavelli, V., Peri, C., & Nobili, S. (1999). Variation in antioxidant
 435 components of tomato during vine and post-harvest ripening. *Journal of the*
 436 *Science of Food and Agriculture*, 79(12), 1583-1588. doi: 10.1002/(SICI)1097-
 437 0010(199909)79:12<1583::AID-JSFA405>3.0.CO;2-J

438 Gonzalez-Aguilar, G. A., Zavaleta-Gatica, R., & Tiznado-Hernandez, M. E. (2007).
 439 Improving postharvest quality of mango 'Haden' by UV-C treatment. *Postharvest*
 440 *Biology and Technology*, 45(1), 108-116. doi: 10.1016/j.postharvbio.2007.01.012

441 Gonzalez-Aguilar, G., Wang, C. Y., & Buta, G. J. (2004). UV-C irradiation reduces
 442 breakdown and chilling injury of peaches during cold storage. *Journal of the*
 443 *Science of Food and Agriculture*, 84(5), 415-422. doi: 10.1002/jsfa.1675

444 Gonzalez-Aguilar, G. A., Villa-Rodriguez, J. A., Ayala-Zavala, J. F., & Yahia, E. M.
 445 (2010). Improvement of the antioxidant status of tropical fruits as a secondary
 446 response to some postharvest treatments. *Trends in Food Science and Technology*,
 447 21(10), 475-482. doi: 10.1016/j.tifs.2010.07.004

448 Grierson, D., & Kader, A. A. (1986). The Tomato Crop—A Scientific Basis for
 449 Improvement. In J. G. Atherton & J. Rudich (Eds.), *Fruit ripening and quality* (pp.
 450 241–280). London: Chapman & Hall.

451 Guerrero-Beltrán, J. A., & Barbosa-Cánovas, G. V. (2004). Reviews: Advantages and
 452 Limitations on Processing Foods by UV Light. *Food Science & Technology*
 453 *International*, 10(3), 137-147. doi: 10.1177/1082013204044359

454 Jagadeesh, S., Charles, M., Gariepy, Y., Goyette, B., Raghavan, G., & Vigneault C.
 455 (2011). Influence of postharvest UV-C hormesis on the bioactive components of
 456 tomato during post-treatment handling. *Food and Bioprocess Technology*,
 457 4(1463–1472), 1463–1472.

458 Jeong, J., Huber, D. J., & Sargent, S. A. (2002). Influence of 1-methylcyclopropene (1-
 459 MCP) on ripening and cell-wall matrix polysaccharides of avocado (*Persea*
 460 *americana*) fruit. *Postharvest Biology and Technology*, 25(3), 241-256. doi:
 461 10.1016/S0925-5214(01)00184-3

462 Kader, A. A. (1986). Effect of postharvest handling procedures on tomato quality. *Acta*
 463 *Horticulturae*, 190, 209–221.

464 Kader, A. A. (2008). Flavor quality of fruits and vegetables. *Journal of the Science of*
 465 *Food and Agriculture*, 88(11), 1863-1868. doi: 10.1002/jsfa.3293

466 Kotíková, Z., Lachman, J., Hejtmánková, A., & Hejtmánková, K. (2011). Determination
 467 of antioxidant activity and antioxidant content in tomato varieties and evaluation
 468 of mutual interactions between antioxidants. *LWT - Food Science and Technology*,
 469 44(8), 1703-1710. doi: <http://dx.doi.org/10.1016/j.lwt.2011.03.015>

470 Li, P., Yin, F., Song, L., & Zheng, X. (2016). Alleviation of chilling injury in tomato fruit
 471 by exogenous application of oxalic acid. *Food Chemistry*, 202, 125-132. doi:
 472 <http://dx.doi.org/10.1016/j.foodchem.2016.01.142>

473 Lichtenthaler, H. K., & Wellburn, A. R. (1983). Determinations of total carotenoids and
 474 chlorophylls a and b of leaf extracts in different solvents. *Biochemical Society*
 475 *Transactions*, 11, 591-592.

476 Liu, C., Cai, L., Han, X., & Ying, T. (2011). Temporary effect of postharvest UV-C
 477 irradiation on gene expression profile in tomato fruit. *Gene*, 486(1–2), 56-64. doi:
 478 <http://dx.doi.org/10.1016/j.gene.2011.07.001>

479 Liu, D., Shi, J., Colina Ibarra, A., Kakuda, Y., & Jun Xue, S. (2008). The scavenging
 480 capacity and synergistic effects of lycopene, vitamin E, vitamin C, and β -carotene
 481 mixtures on the DPPH free radical. *LWT - Food Science and Technology*, 41(7),
 482 1344-1349. doi: <http://dx.doi.org/10.1016/j.lwt.2007.08.001>

483 Liu, L. H., Zabaras, D., Bennett, L. E., Aguas, P., & Woonton, B. W. (2009). Effects of
 484 UV-C, red light and sun light on the carotenoid content and physical qualities of
 485 tomatoes during post-harvest storage. *Food Chemistry*, 115(2), 495-500. doi:
 486 <http://dx.doi.org/10.1016/j.foodchem.2008.12.042>

487 Lopez Camelo, A. F., & Gomez, P. A. (2004). Comparison of color indexes for tomato
 488 ripening. *Horticultura Brasileira*, 22(3), 534-537. doi:
 489 <http://dx.doi.org/10.1590/S0102-05362004000300006>.

490 Maharaj, R., Arul, J., & Nadeau, P. (1999). Effect of photochemical treatment in the
 491 preservation of fresh tomato (*Lycopersicon esculentum* cv. Capello) by delaying
 492 senescence. *Postharvest Biology and Technology*, 15(1), 13-23. doi:
 493 [10.1016/S0925-5214\(98\)00064-7](http://dx.doi.org/10.1016/S0925-5214(98)00064-7)

494 Malundo, T. M. M., Shewfelt, R. L., & Scott, J. W. (1995). Flavor quality of fresh tomato
 495 (*Lycopersicon esculentum* Mill.) as affected by sugar and acid levels. *Postharvest*

496 *Biology and Technology*, 6(1–2), 103-110. doi: <http://dx.doi.org/10.1016/0925->
497 5214(94)00052-T

498 Pataro, G., Sinik, M., Capitoli, M. M., Donsi, G., & Ferrari, G. (2015). The influence of
499 post-harvest UV-C and pulsed light treatments on quality and antioxidant
500 properties of tomato fruits during storage. *Innovative Food Science & Emerging*
501 *Technologies*, 30(0), 103-111. doi: 10.1016/j.ifset.2015.06.003

502 Pedro, A. M. K., & Ferreira, M. M. C. (2007). Simultaneously calibrating solids, sugars
503 and acidity of tomato products using PLS2 and NIR spectroscopy. *Analytica*
504 *Chimica Acta*, 595(1–2), 221-227. doi:
505 <http://dx.doi.org/10.1016/j.aca.2007.03.036>

506 Pinheiro, J., Alegria, C., Abreu, M., Gonçalves, E. M., & Silva, C. L. (2015). Use of UV-
507 C postharvest treatment for extending fresh whole tomato (*Solanum lycopersicum*,
508 cv. Zinac) shelf-life. *Journal of Food Science and Technology*, 52(8), 5066-5074.
509 doi: <http://dx.doi.org/10.1007/s13197-014-1550-0>

510 Pristijono, P. (2007). *Use of nitric oxide to extend the postharvest life of fresh-cut and*
511 *intact fruits and vegetables*. (PhD), The University of Newcastle, Australia.

512 Saltveit, M. E. (2005). Postharvest biology and handling. In E. Heuvelink (Ed.), *Tomatoes*
513 (pp. 305–324.). Oxfordshire, UK: CABI Publishing.

514 Scalbert, A., Monties, B., & Janin, G. (1989). Tannins in wood: comparison of different
515 estimation methods. . *Journal of Agricultural and Food Chemistry*, 37, 324-329.

516 Scibisz, I., Reich, M., Bureau, S., Gouble, B., Causse, M., Bertrand, D., & Renard, C. M.
517 G. C. (2011). Mid-infrared spectroscopy as a tool for rapid determination of
518 internal quality parameters in tomato. *Food Chemistry*, 125(4), 1390-1397. doi:
519 10.1016/j.foodchem.2010.10.012

Severo, J., Tiecher, A., Pirrello, J., Regad, F., Latche, A., Pech, J. C., Bouzayen, M., and Rombaldi, C.V. (2015). UV-C radiation modifies the ripening and accumulation of ethylene response factor (ERF) transcripts in tomato fruit. *Postharvest Biology and Technology*, 102(0), 9-16. doi: 10.1016/j.postharvbio.2015.02.001

Singleton, V. L., & Rossi, J. A. (1965). Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. *American Journal of Enology and Viticulture*, 16, 144-158.

Stevens, C., Liu, J., Khan, V. A., Lu, J. Y., Wilson, C. L., Igwegbe, E. C. K., Kawbe, M.K., Chalutz, E. and Droby, S. (1998). Application of Hormetic UV-C for Delayed Ripening and Reduction of Rhizopus Soft Rot in Tomatoes: the Effect of Tomatine on Storage Rot Development. *Journal of Phytopathology*, 146(5/6), 211. doi: 10.1111/1439-0434.ep6402166

Stevens, C., Liu, J., Khan, V. A., Lu, J. Y., Kabwe, M. K., Wilson, C. L., Igwegbe, E.C.K., Chalutz, E., and Droby, S. (2004). The effects of low-dose ultraviolet light-C treatment on polygalacturonase activity, delay ripening and Rhizopus soft rot development of tomatoes. *Crop Protection*, 23(6), 551-554. doi: 10.1016/j.cropro.2003.10.007

Tiecher, A., de Paula, L. A., Chaves, F. C., & Rombaldi, C. V. (2013). UV-C effect on ethylene, polyamines and the regulation of tomato fruit ripening. *Postharvest Biology and Technology*, 86, 230-239. doi: 10.1016/j.postharvbio.2013.07.016

Wills, R. B. H., & Ku, V. V. V. (2002). Use of 1-MCP to extend the time to ripen of green tomatoes and postharvest life of ripe tomatoes. *Postharvest Biology and Technology*, 26(1), 85-90. doi: 10.1016/S0925-5214(01)00201-0

543 Wills, R. B. H., Warton, M. A., & Ku, V. V. V. (2000). Ethylene levels associated with
544 fruit and vegetables during marketing. *Australian Journal of Experimental*
545 *Agriculture*, 40(3), 465-470.

546 Zanfini, A., Corbini, G., La Rosa, C., & Dreassi, E. (2010). Antioxidant activity of tomato
547 lipophilic extracts and interactions between carotenoids and alpha-tocopherol in
548 synthetic mixtures. *Lwt-Food Science and Technology*, 43(1), 67-72. doi:
549 10.1016/j.lwt.2009.06.011

550

551 **Table 1.** Quality parameters of tomatoes at the beginning of the experiment. Values
552 represent the mean and standard error (S.E.) of three replicates consisting of 10
553 tomatoes each replicate.

Parameter	Value
Colour (°Hue)	116.0 ± 0.2
Ethylene (µl C ₂ H ₄ .kg ⁻¹ .h ⁻¹)	0.17 ± 0.07
Respiration rate (ml CO ₂ .kg ⁻¹ .h ⁻¹)	5.11 ± 0.26
SSC (°Bx)	4.2 ± 0.2
TA (% citric acid)	1.02 ± 0.08
Ratio TSS to TA	4.2 ± 0.2
Firmness (N)	42.9 ± 0.8
Chlorophyll (mg/L)	0.46 ± 0.03
Lycopene (mg/g f.w)	1.27 ± 0.06
TPC (mg Gallic acid equiv /g f.w)	0.62 ± 0.02
Total antioxidant activity (% DPPH scavenging activity)	18.2 ± 1.3

554
555
556
557
558
559
560

561
562 **Table 2.** Soluble solids content (SSC), titratable acidity (TA), and SSC/TA (or
563 sugar/acid) ratio of fully ripe tomato after treated with UV-C, 1-MCP and UV-C
564 combined with 1-MCP, followed by storage in in continuous air containing $0.1 \mu\text{l l}^{-1}$
565 ethylene at 20°C.
566

Treatments	SSC (°Brix)	TA (% citric acid)	SSC/TA ratio
Control	4.1	0.51	8.1
UV-C	3.9	0.50	7.9
1-MCP	3.9	0.50	7.8
1-MCP + UV-C	4.0	0.50	8.1
<i>LSD (5%)</i>	± 0.4	± 0.11	± 0.4

Values are the mean of 3 replicates

567
568
569
570

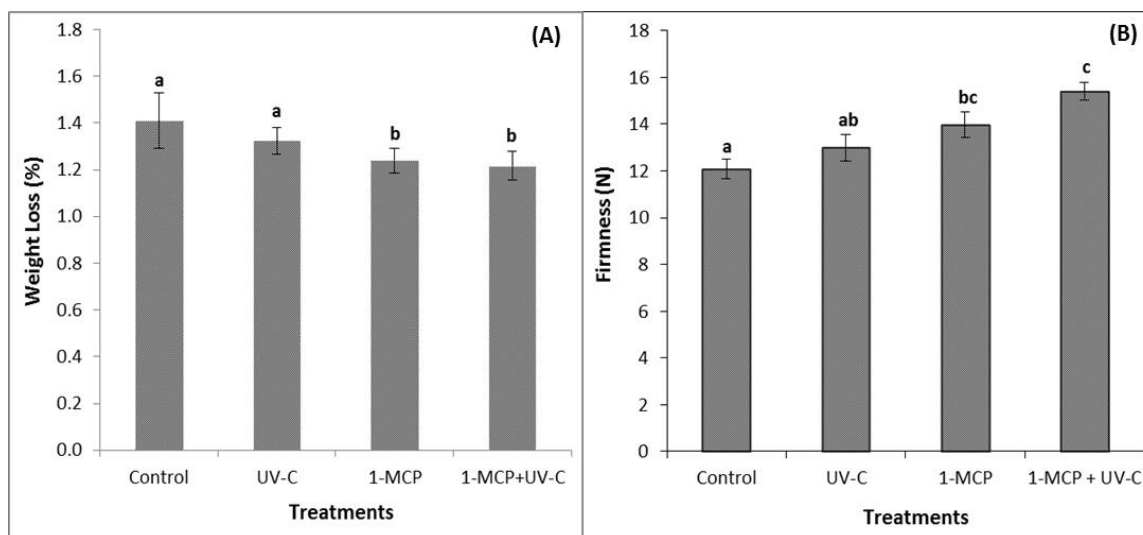


Figure 1. Weight loss (A) and firmness (B) of tomato after treated with UVC, 1-MCP and UV-C integrated with 1-MCP, followed by storage in continuous air containing $0.1 \mu\text{l.l}^{-1}$ ethylene at 20°C .

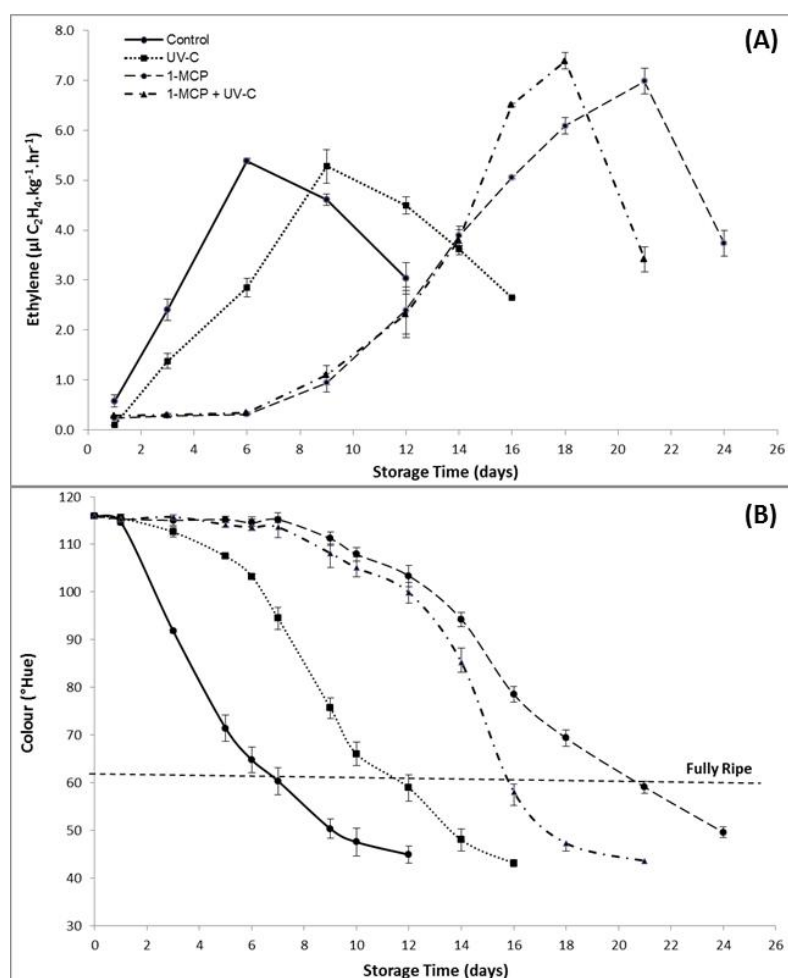


Figure 2. Ethylene production (A) and skin colour (B) of tomato after treated with UV-C, 1-MCP and UV-C combined with 1-MCP, followed by storage in continuous air containing $0.1 \mu\text{l l}^{-1}$ ethylene at 20°C .

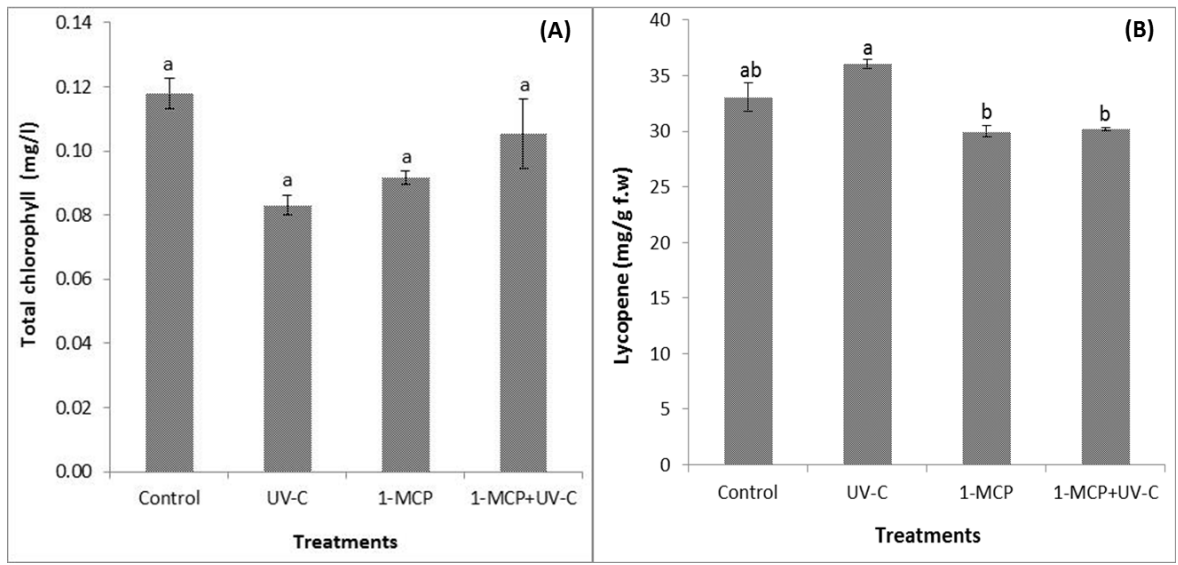


Figure 3. Total chlorophyll (A) and lycopene content (B) of fully ripe tomato after treated with UV-C, 1-MCP and UV-C combined with 1-MCP, followed by storage in continuous air containing $0.1 \mu\text{l l}^{-1}$ ethylene at 20°C .

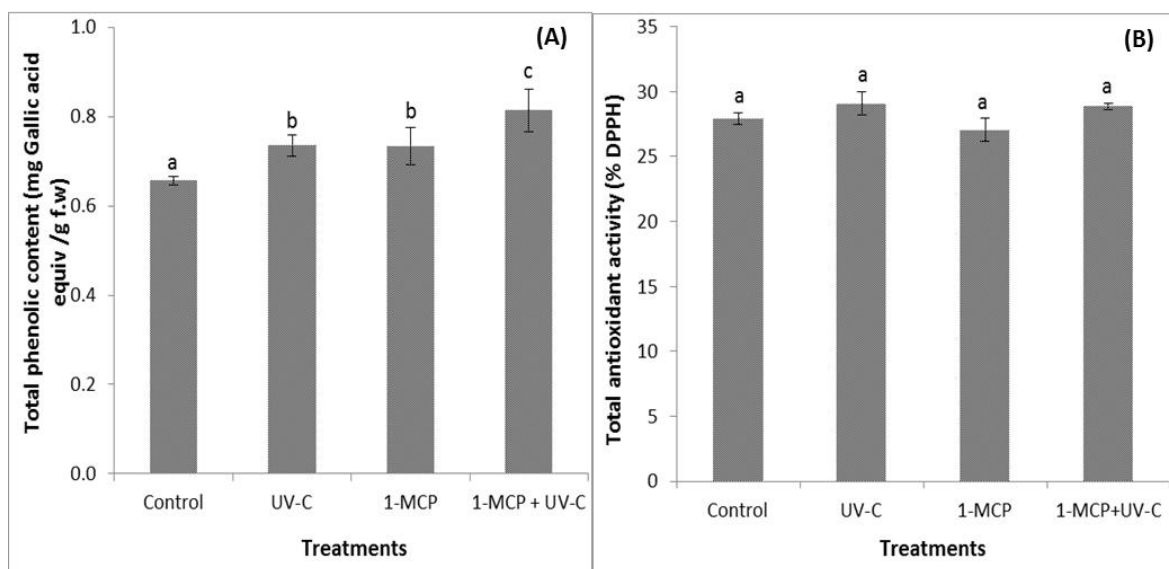


Figure 4. Total phenolic content (A) and total antioxidant activity (B) of fully ripe tomato after treated with UV-C, 1-MCP and UV-C combined with 1-MCP, followed by storage in continuous air containing $0.1 \mu\text{l l}^{-1}$ ethylene at 20°C .